1948-05

Investigation of methods of plotting resistance of ships to simplify preliminary design power studies

Nicholson, William M.; Hoof, Wayne; Nicholson, William M.; Hoof, Wayne

Massachusetts Institute of Technology

http://hdl.handle.net/10945/6461

INVESTIGATION OF METHODS OF PLOTTING RESISTANCE OF SHIPS TO SIMPLIFY PRELIMINARY DESIGN POWER STUDIES

WILLIAM M. NICHOLSON
WAYNE HOOF

Cambridge, Massachusetts,
May 20, 1948.

Professor J. S. Newell,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Dear Sir:

In accordance with the requirements for the degree of Master of Science in Naval Construction and Engineering, we submit herewith a thesis entitled, "Investigation of Methods of Plotting Resistance of Ships to Simplify Preliminary Design Power Studies."

Respectfully,

INVESTIGATION OF METHODS OF PLOTTING RESISTANCE OF SHIPS TO SIMPLIFY PRELIMINARY DESIGN POWER STUDIES

By

William M. Nicholson
Lieut. Commander, U. S. Navy
B.S., U.S. Naval Academy, 1941

Wayne Hoof
Lieut. Commander, U.S. Navy
B.S., U.S. Naval Academy, 1941

Submitted in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE IN NAVAL CONSTRUCTION

AND ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1948

ACKNOWLEDGMENT

The authors wish to express their appreciation to Professor George C. Manning for his suggestion of the idea on which this thesis is based, and for his continued interest in its development.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SYMBOLS

Δ Displacement in tons

B Beam in feet

H Draft " "

L Length " "

V Speed in Knots

ℓ Longitudinal Coefficient $\frac{35\Delta}{mBHL}$.

ℓ_1 Nearest plotted value of ℓ below actual hull.

ℓ_2 Nearest plotted value of ℓ above actual hull.

m Midship Section Coefficient $\frac{\text{section area}}{BH}$

d Displacement - length coefficient $\frac{\Delta}{(L/100)^3}$

f Tideman's constant for frictional resistance.

Rr Residual resistance in pounds per ton of displ.

Rf Frictional " " " " " " "

Rc Total " " " " " " "
(for mean hull B/H3.0 and L 500 ft.)

Rt Total Resistance in pounds per ton of displ.
(corrected for actual hull)

x Ratio Rf/Rt

α Length correction to Rf for variation from L 500 ft.

C' Correction to Rc for B/H variation of + 1.0 from mean value 3.0.

C Correction to Rc for B/H of actual hull.

A Length correction to be applied to (Rc + C)

SUMMARY

This thesis comprises an attempt to obtain a simple, concise method of determining resistance to ship propulsion in the early stages of design work where frequent changes in characteristics are made and qualitative rather than exact quantitative information is required. The line of investigation has been reorganization of the data given in Taylor's contours of resistance and elimination of variables which have minor effects wherever possible. It has been found possible to plot contours of total resistance vs d and $V/\sqrt{L}$ for a mean hull at various values of ℓ (figures V to XVII) and to provide two simple corrections, one for length (figure III) and one for B/H (figure IV) which will give results accurate within $2\frac{1}{2}$% of Taylor's series (See table IV). We thus have a total of 15 charts, only 4 of which are required for any specific hull.

Use of these charts may be reduced to the following simple equation:

$$Rt = [Rc + C]\ A \qquad (1)$$

where Rc is obtained from figures V to XVII.

C = (B/H - 3.0) C' and C' is from fig. IV

A is obtained from figure III.

Figures V to XVII may be used without interpolation by using the nearest value of ℓ with a difference from interpolated values of 5% or less - average about 2% for median values of ℓ (.55, .65, etc.) If a linear interpolation is made, the total number of charts required to cover the entire range of

variables can be reduced to 7 with negligible sacrifice in accuracy. This is a considerable improvement over the 56 charts required in Taylor.

The authors have found use of these curves much simpler, quicker, and less subject to errors of reading and interpolation than the curves used in Taylor. They are not intended to improve on the accuracy of Taylor's data, and of course they will not allow for special variations in hull form used to improve on the standard series such as transom sterns and bulbous bows. The work should be very useful, however, in any problems involving estimates of resistance, especially in preliminary design work.

INTRODUCTION

In the preparation of any preliminary design, one of the tedious jobs is the frequent determination of power requirements at the desired maximum speed and cruising speed as hull coefficients are changed. The desired speeds are generally given, and they are almost invariably at values of $V/\sqrt{L}$ not plotted in Taylor's curves so that an awkward four way interpolation is required to get the resistance. High accuracy is not essential at this stage in the development of a design, hence it appeared possible to develop a quicker means of determining resistance variations as the characteristics are changed in the preliminary stages. A survey of literature on the subject of resistance revealed only one such attempt - a set of curves developed by Mr. F. Weckscher of the Hamburg Model Basin. These curves, printed in an article by Mr. M. M. Lachowski in the Marine Engineering and Shipping Review of March 1947, covered a range of $V/\sqrt{L}$ from .60 to 1.10 and plotted speed contours on an abscissa of length and an ordinate of $\frac{Rr}{Rt}$. This gives a ready, though very rough, method of estimating E.H.P. The primary objection to general use of such a simple set of curves lies in the complete disregard of variations in coefficients of form. A preliminary investigation indicated that considerable simplification of Taylor's curves could be achieved at very little expense of accuracy - the curves developed from this investigation are presented in this thesis.

PROCEDURE

"The Speed and Power of Ships," by D. W. Taylor forms the basis for all the data used in the development of this thesis. The frictional resistance data was obtained from Taylor's figure 188 and the residual resistance was obtained from Taylor's contours of residual resistance.

A. Limitation of Variables.

The first step in the development of the thesis was to select the coefficients of form to be used in the preparation of curves, and to limit the range of these coefficients as far as practical. To this end, a table of representative characteristics (Table I) was prepared, covering types of ships in actual service. For simplification of both plotting and use it is desirable to fix as many variables as possible. It was decided that a mean value of B/H could be used, thus eliminating one interpolation required in Taylor's curves. A mean B/H value of 3.0 was selected. It was also decided to cover values of d from 50 to 190, $V/\sqrt{L}$ from .50 to 1.80, and ℓ from .56 to .80. It was not apparent how large the effect of variation of m would be but tentatively it was decided to leave it out of the calculations.

B. Method of Plotting

The next question was how the data could best be plotted to simplify Taylor's presentation. $V/\sqrt{L}$ was selected as the most desirable abscissa as it is always the basis for

plotting EHP data. Following the lead of Mr. Hecksher's plot, referred to in the introduction, preliminary rough plots were made up with $\frac{Rr}{Rf}$ and $\frac{Rr}{Rt}$ as ordinates and for various values of ℓ and d. These resistance factors were also tried on coordinates of ℓ and d for various values of $V/\sqrt{L}$ but the results were not promising enough to warrant refinement. Use of these ratios requires computation of Rf and provides little or no simplification in the number of operations that must be performed to arrive at the total resistance. After a study of these preliminary forms it was decided that the most promising line of effort was to plot contours of total resistance on d and $V/\sqrt{L}$ for successive values of ℓ. If these values of ℓ are selected close enough together it makes it possible to use the nearest charted value of ℓ to the actual hull being considered with good accuracy. If, on the other hand, it is more desirable to limit the number of charts a smaller number of values of ℓ should be used and the actual results obtained by interpolation. It was decided that intervals of .02 would be close enough to permit approximate use without interpolation and yet would cover the desired range without too many plots. For determination of Rf it was decided to use a length of 500 ft. and a wetted surface coefficient of 15.4 as used in Taylor's figure 108.

The resistance data presented in Taylor's curves was picked off in tabulated form for use in preparing the curves. (Table II in the appendix is a sample of this form. Originals are filed in the thesis notebook). A complete

set of resistance curves was prepared to large scale, plotting curves of Rt vs $V/\sqrt{L}$ for d values of 50, 70, 90, 110, 130, 150, 170, & 190. One set of these curves was prepared for each value of ℓ from .54 to .80 in increments of .02. (These curves also are filed in the Thesis notebook). Figure I is a sample, to small scale, to illustrate the method. It will be noted that a larger scale was used for accuracy below $V/\sqrt{L}$ of about 1.00. The Rc contours (Rt for the selected mean coefficients) were then plotted by picking off the data from the master curves as illustrated by figures I and II. The finished contours are included here as figures V to XVII under Results.

C. <u>Corrections for L, B/H,</u>

It is obvious that several errors arising from use of mean B/H and L are present if these contours of Rc are to be used for a variety of hulls - some of which may differ widely from the mean coefficients used here. It was felt that considerable improvement could be made by introducing two simple corrections - one for variation of B/H from the mean value of 3.0 and the other for variation of length from 500 ft.

The effect of length variation on frictional resistance is determined by the equation

$$\alpha = \frac{f}{f_{500}} \left(\frac{500}{L} \right)^{.085} \qquad \text{(see fig. 148 Taylor)} \quad (1)$$

The effect of this correction on total resistance is determined by the proportion of Rf to Rt. This was averaged for various values of d and ℓ and plotted vs. $V/\sqrt{L}$ (fig. XVIII).

FIGURE I

LONG COEF ℓ - .62

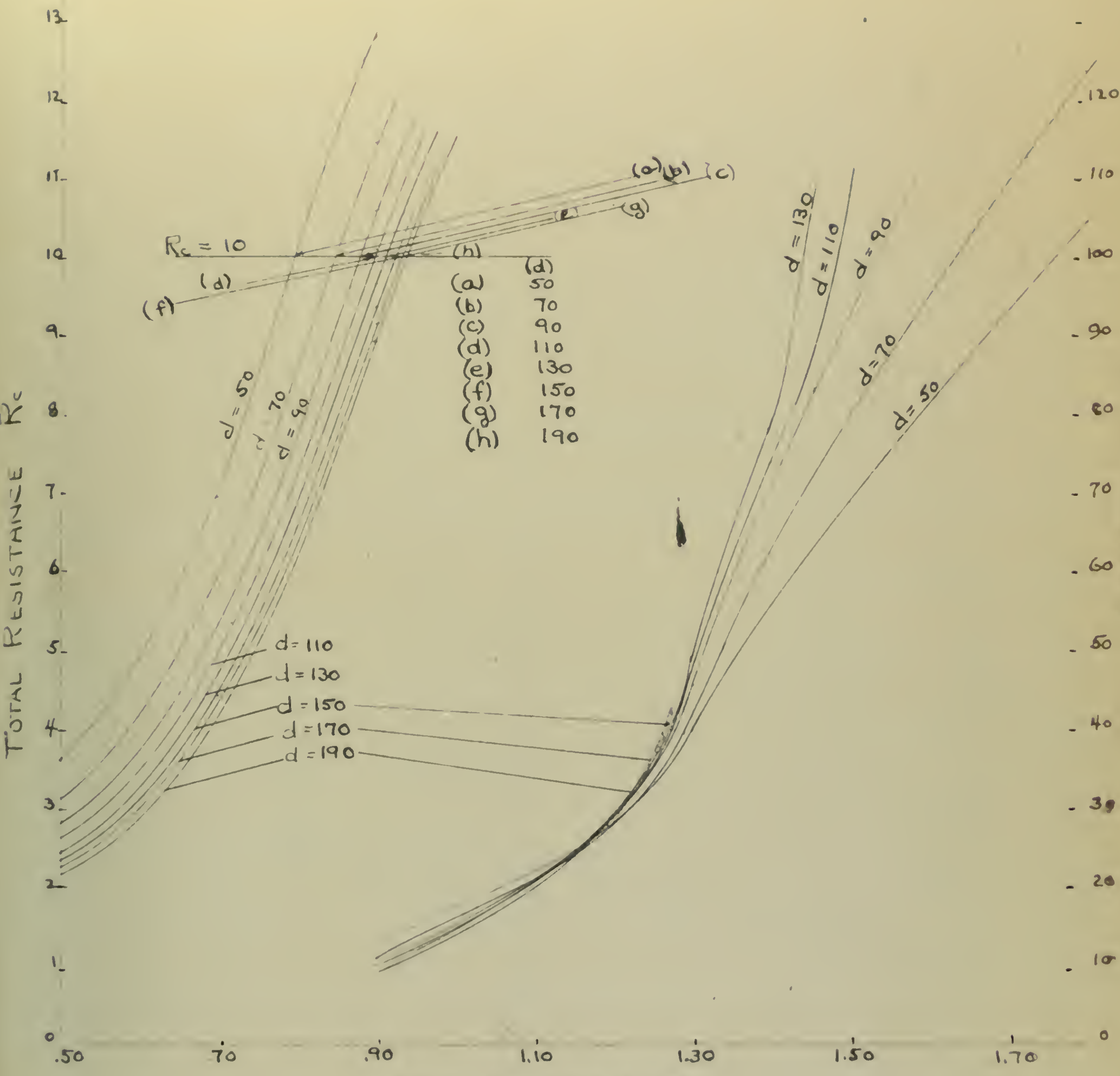


FIGURE SHOWING METHOD OF PLOTTING VALUES OF R_c (TABULATED FROM TAYLOR'S "SPEED + POWER OF SHIPS")

AND METHOD OF TRANSFERRING POINTS TO CONTOURS OF RESISTANCE

MAY 11 48

FIGURE II

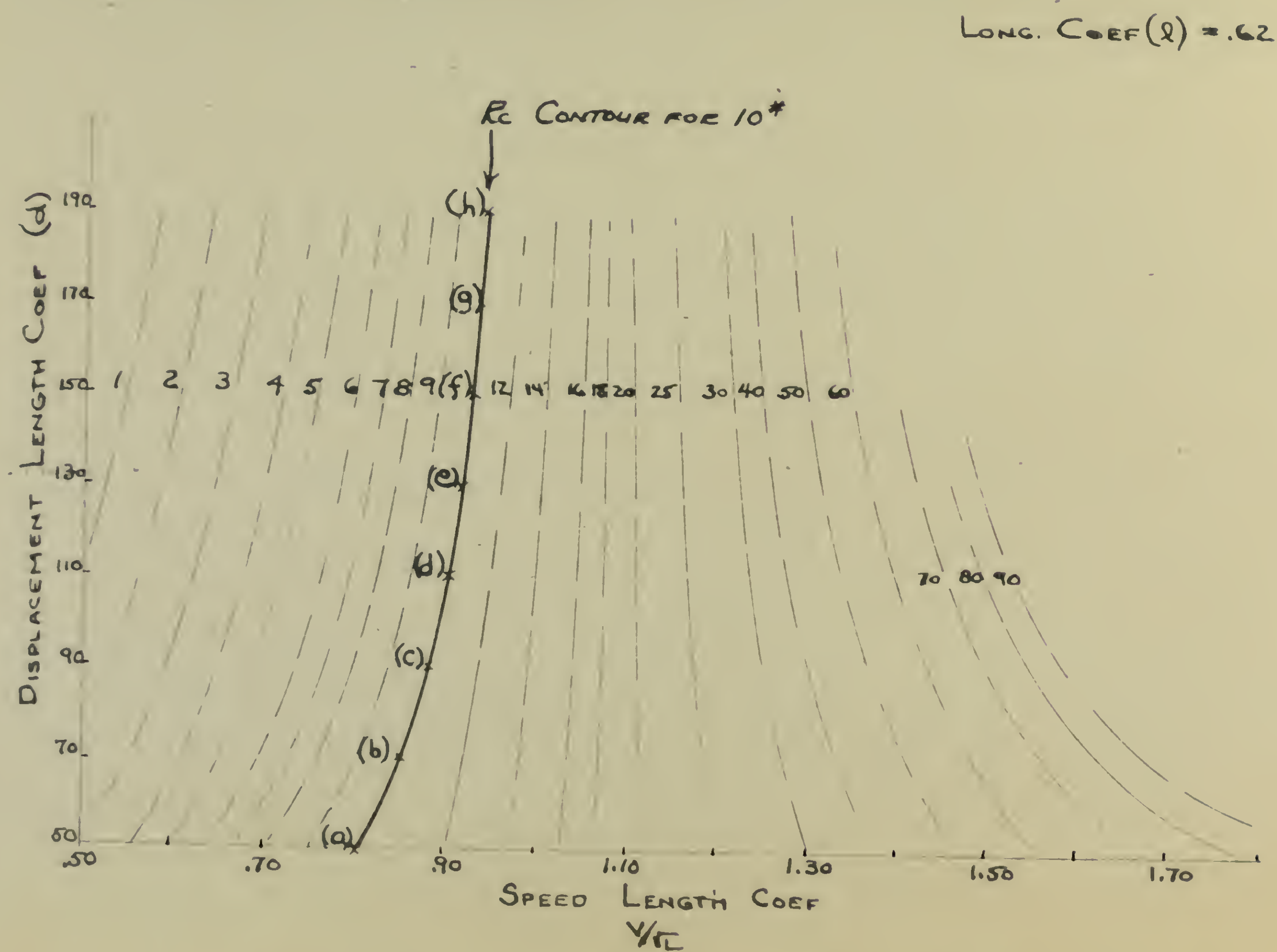


FIGURE SHOWING METHOD OF PLOTTING CONTOURS OF TOTAL RESISTANCE R_c
(SEE FIGURE I)

We thus have a specific proportion for each $V/\sqrt{L}$ and this proportion may be combined with the results of equation (2) in the form of a simple nomograph which yields the average correction A (figure III under results). A more detailed discussion of this correction is given in the appendix.

Variation of B/H has two effects - one on the value of the wetted surface coefficient and one on the value of Rr. The effect on wetted surface coefficient - and hence on Rf is of the order of 2% or less for normal values of [illegible]. The effect on total resistance is of course smaller than this - especially at moderate to large values of $V/\sqrt{L}$. This is considered of "second order" smallness in an approximate treatment. The effect on Rr, however, is quite large - it may well amount to about 10% of the total resistance and it is therefore essential to correct for it if the method is to provide reasonable accuracy. Several methods of plotting a correction were tried and the final one selected was obtained by graphically averaging the correction for several values of ℓ and plotting this average correction vs d and $V/\sqrt{L}$. The details of this development are covered in the appendix and by figures XIX, and XX. We thus have the advantage of using the same coordinates as the contours of Rc. This "average" correction for B/H is plotted in fig. IV for a unit variation of B/H from the mean value 3.0. The value picked off the figure must be multiplied by the difference between the actual B/H and 3.0 before it is added to Rc. (See equation (1)).

The variation of resistance with the midship section

coefficient m is the only variable unaccounted for. This variable may be considered in the same manner as the effect of B/H on the wetted surface coefficient. Here again we have a "second order" effect and it is neglected in this development. An examination of figure 20 in Taylor will show these effects. The omission of these second order effects is justified by the results obtained.

RESULTS

The results of this study are presented graphically by figures III through XVII. These plots provide a quick and simple means of determining preliminary power requirements on the basis of Taylor's Standard Series. Figures V to XVII are contours of Rc vs d and $V/\sqrt{L}$ for values of ℓ from .56 to .80, a mean B/H of 3.0 and a mean length of 500 ft. Figure IV gives the correction C' which, when multiplied by (B/H - 3.0), gives the value C which must be added to Rc to correct for the actual value of B/H. Figure III gives the length correction, A, which, when multiplied by (Rc + C), gives the actual value of Rt.

Accuracy, of course, is the first question to be considered in using a set of curves such as these. The resistance of hulls of normal form may be determined from these curves with an expected error (based on Taylor's series) of not more than 2½%, which is certainly close enough for preliminary studies. Results for both Taylor's Series and this set of curves over a wide range of representative hulls are given for comparison in the appendix (table IV).

In order to demonstrate the use of these curves and equation (1), assume that we need the power requirements at full speed for a preliminary design of the following characteristics (typical of a transatlantic passenger liner)

L = 800 ft.	Displ. = 40,000 tons	$V/\sqrt{L}$ = .928
B = 95 "	Vmax = 26.25 knots	$B/H - 3.0$ = .14
H = 30 "	d = 77.[illegible]	$\frac{\ell-\ell_1}{.02}$ = .25
ℓ = .625	B/H = 3.14	

Using 2 charts and interpolating we proceed as follows:

from fig. IX (for ℓ_2 .64) we obtain Rc_2 = 13.0

from fig. VIII (for ℓ_1 .62) we obtain Rc_1 = 12.6

Difference = .4

$\frac{\ell-\ell_1}{.02}$ x Diff. = Corr. = .1

$R_c = R_{c1}$ + Corr. = 12.7

We now obtain C' from fig. IV C' = .75

then C = (B/H - 3.0)C' = .14 (.75) = + .10

Rc + C = 12.8

Next obtain length corr. A from fig. III = .97

Rt = A(Rc + C) = .97 (12.8) = 12.4 lbs./ton *

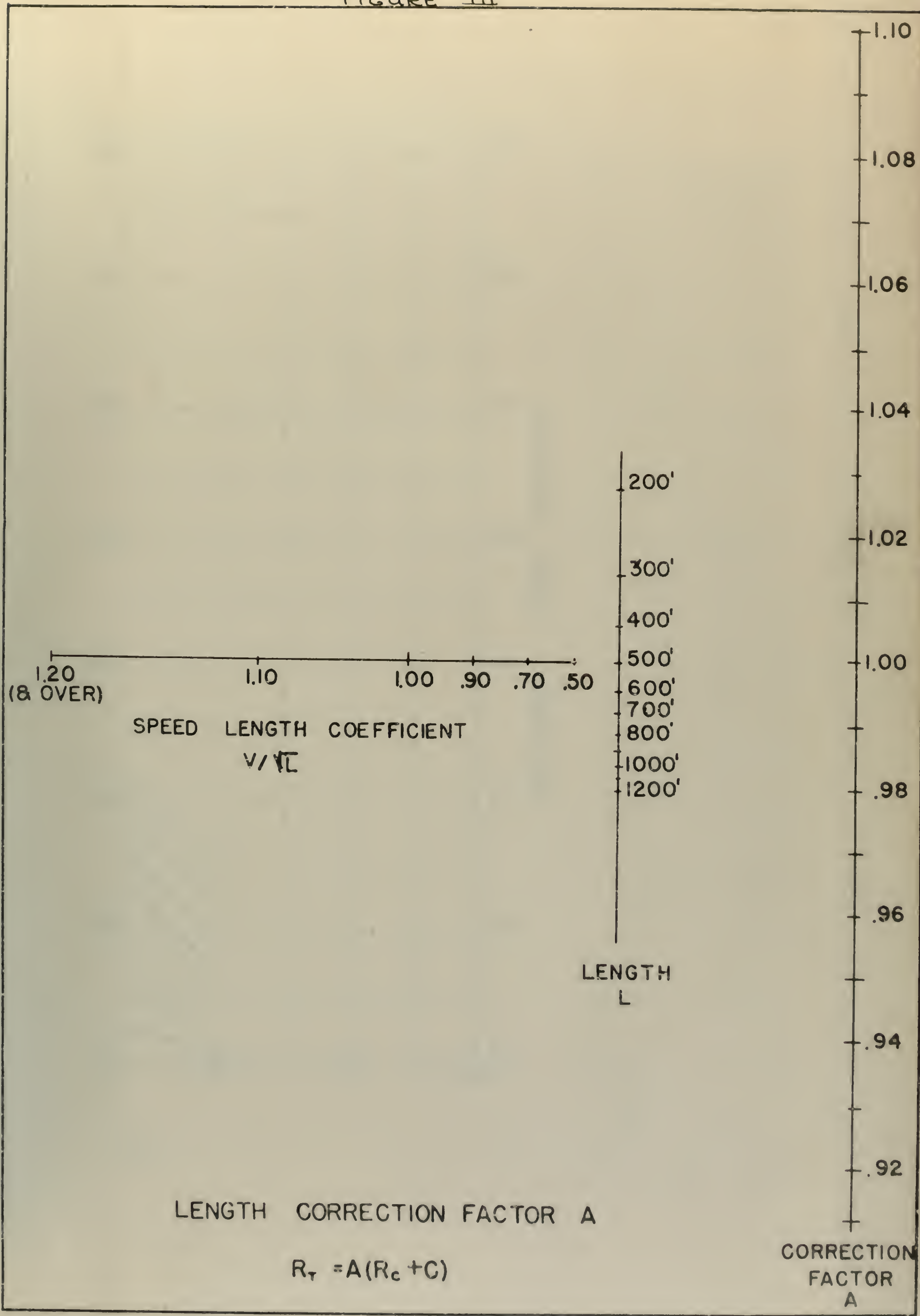
* Taylor's Series, for the same ship, gives 12.6 lbs/ton

If it is not desired to interpolate, the nearest value of ℓ may be used and this simplified procedure requires only the following steps:

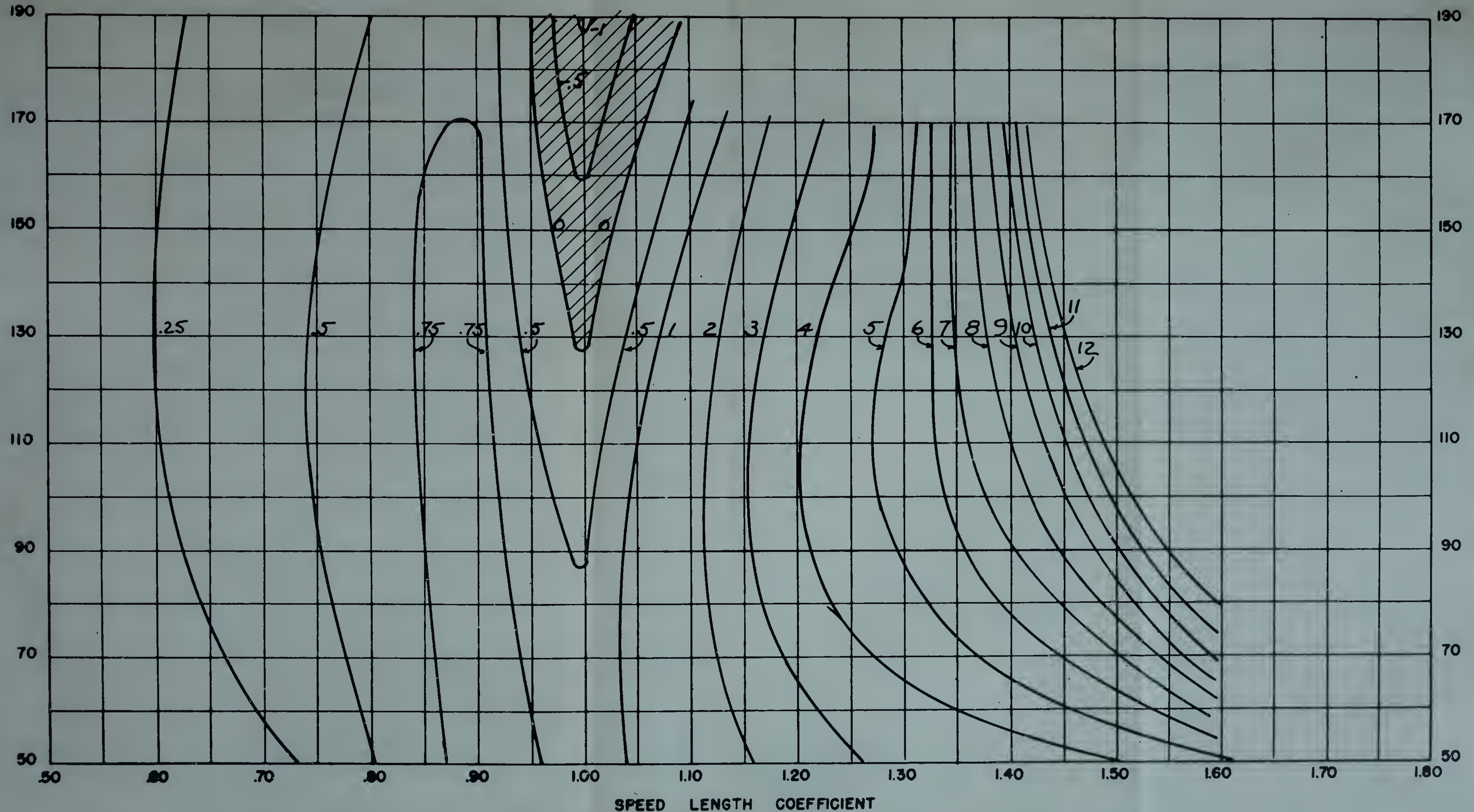
from fig. VIII obtain R_c	12.6
from fig. IV obtain C'	.75
$C = (B/H - .30)\,C'$	.10
$R_c + C$	12.7
from fig. III obtain A	.97
RA	12.32

The figure of 12.32 obtained without interpolation, compared to 12.29 from the interpolated data shows a difference of only .25%, which is quite satisfactory. The difference, which here reduces the error from Taylor's series, is just as likely to increase the error in other cases. This effect is discussed in the next section, and can be seen clearly in Table IV.

FIGURE III

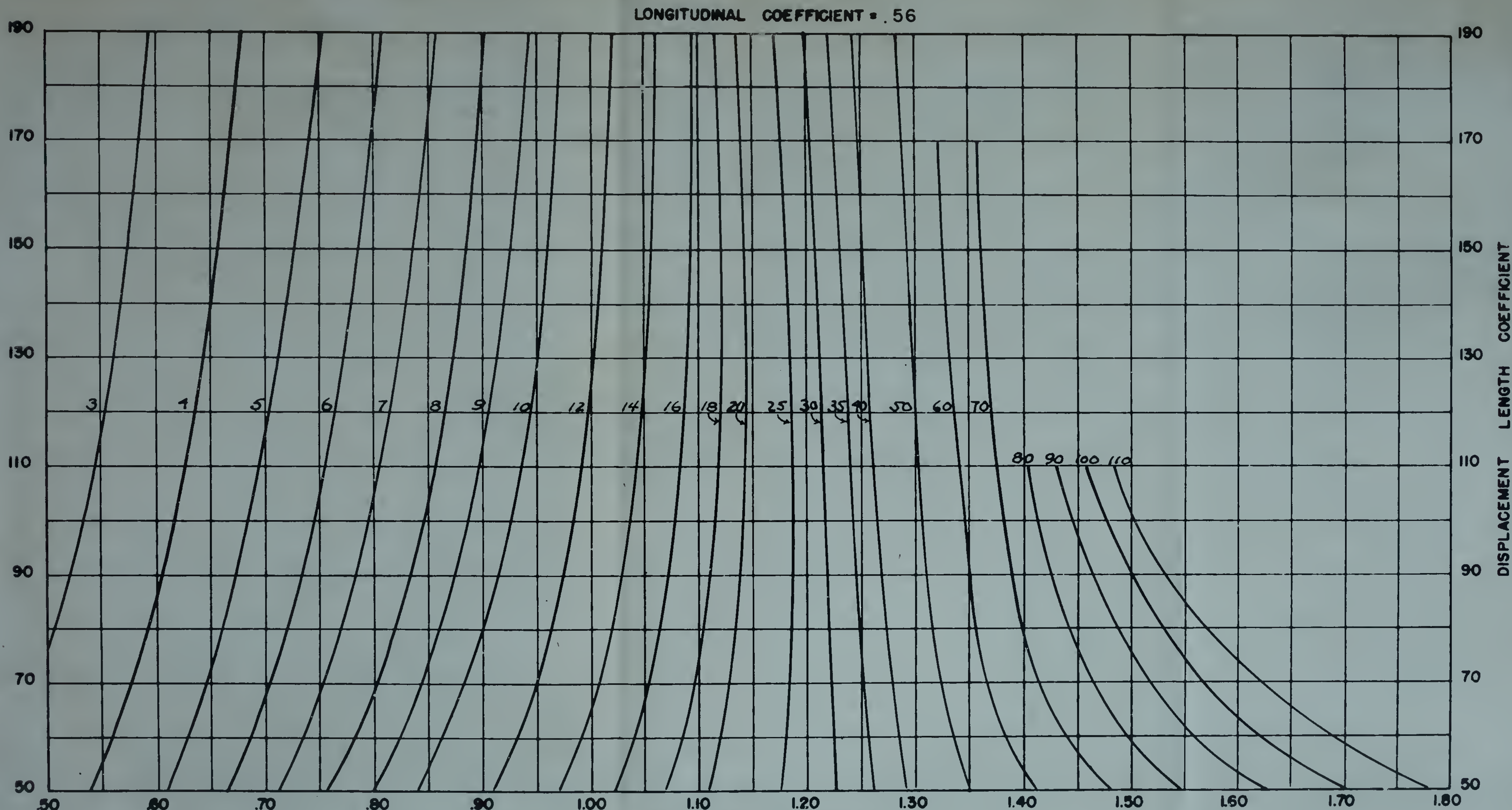


WH
5-18-48



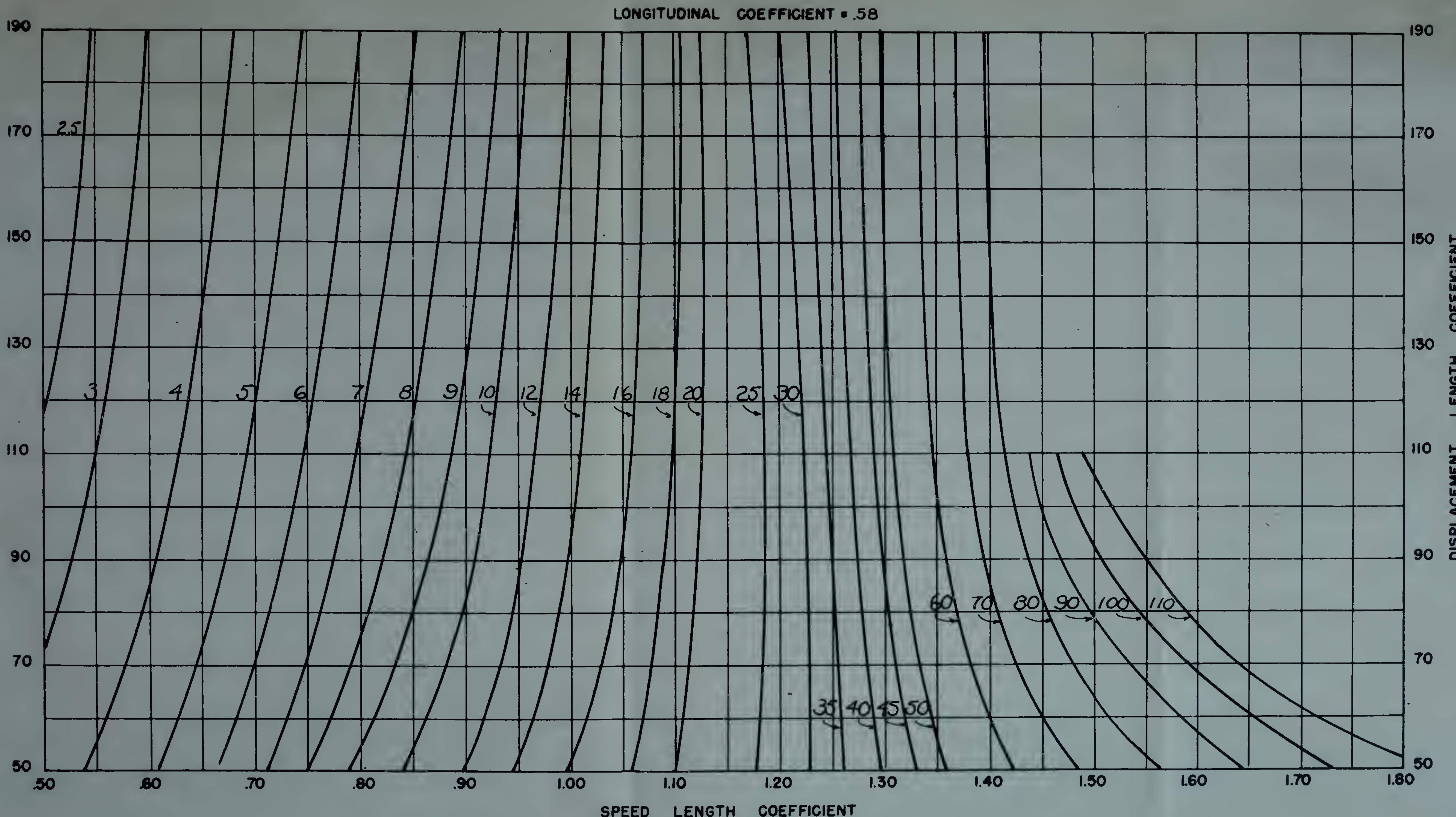
B/H CORRECTION TO TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT (C')
TOTAL B/H CORRECTION (C) = C'(B/H-3.0)

Bsn.N.S.-5-10-48-25



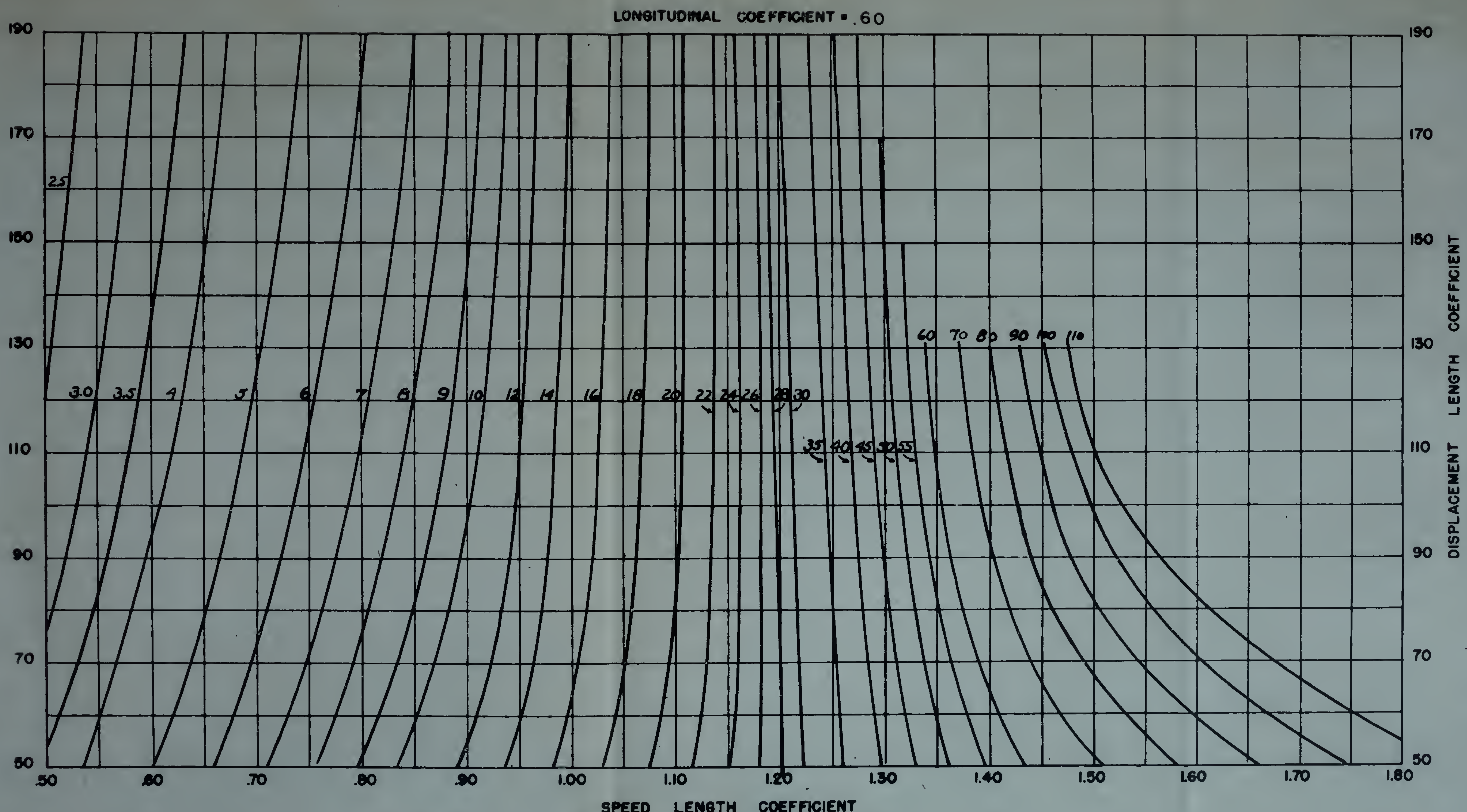
Bsn.N.S.-5-10-48-25

CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT



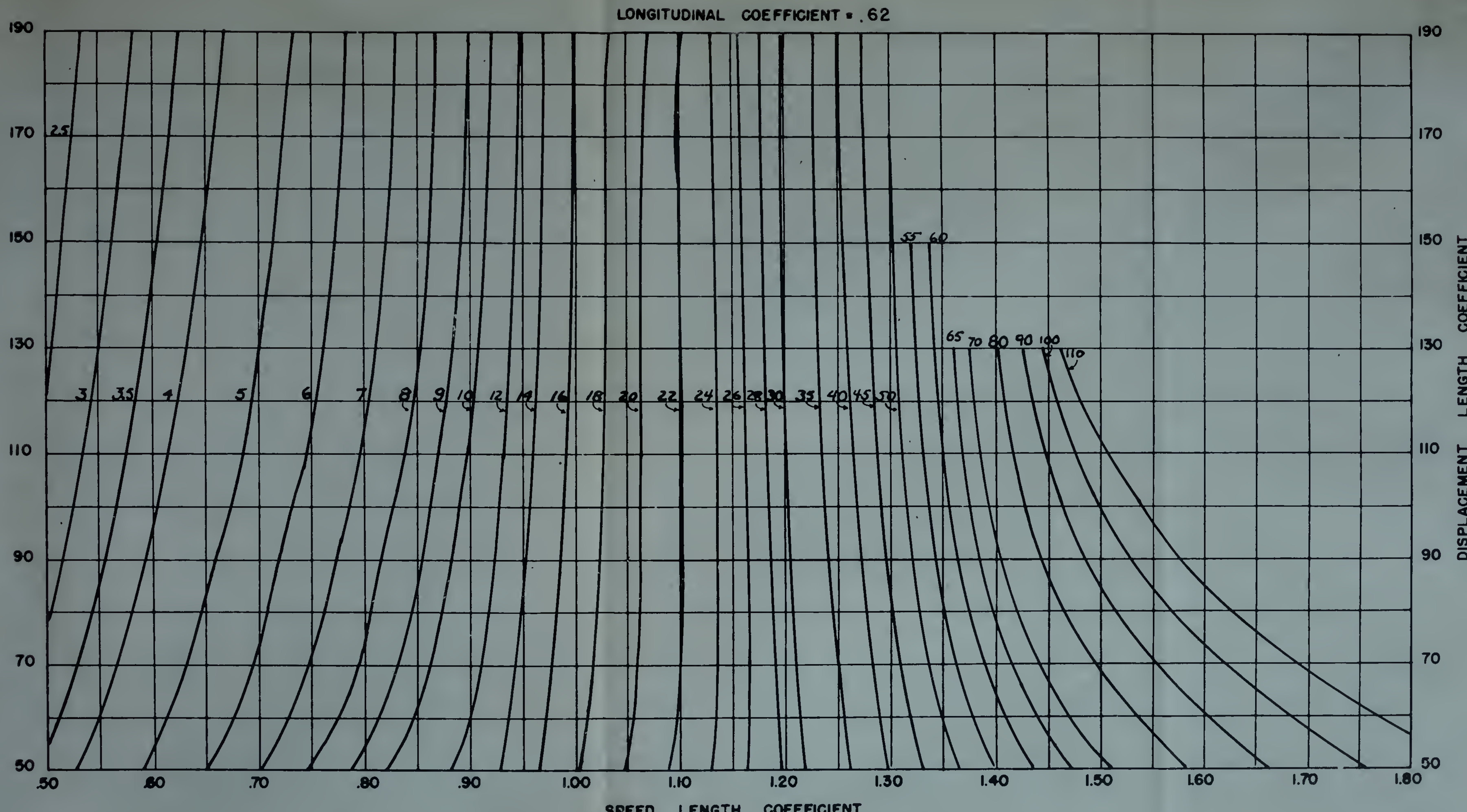
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



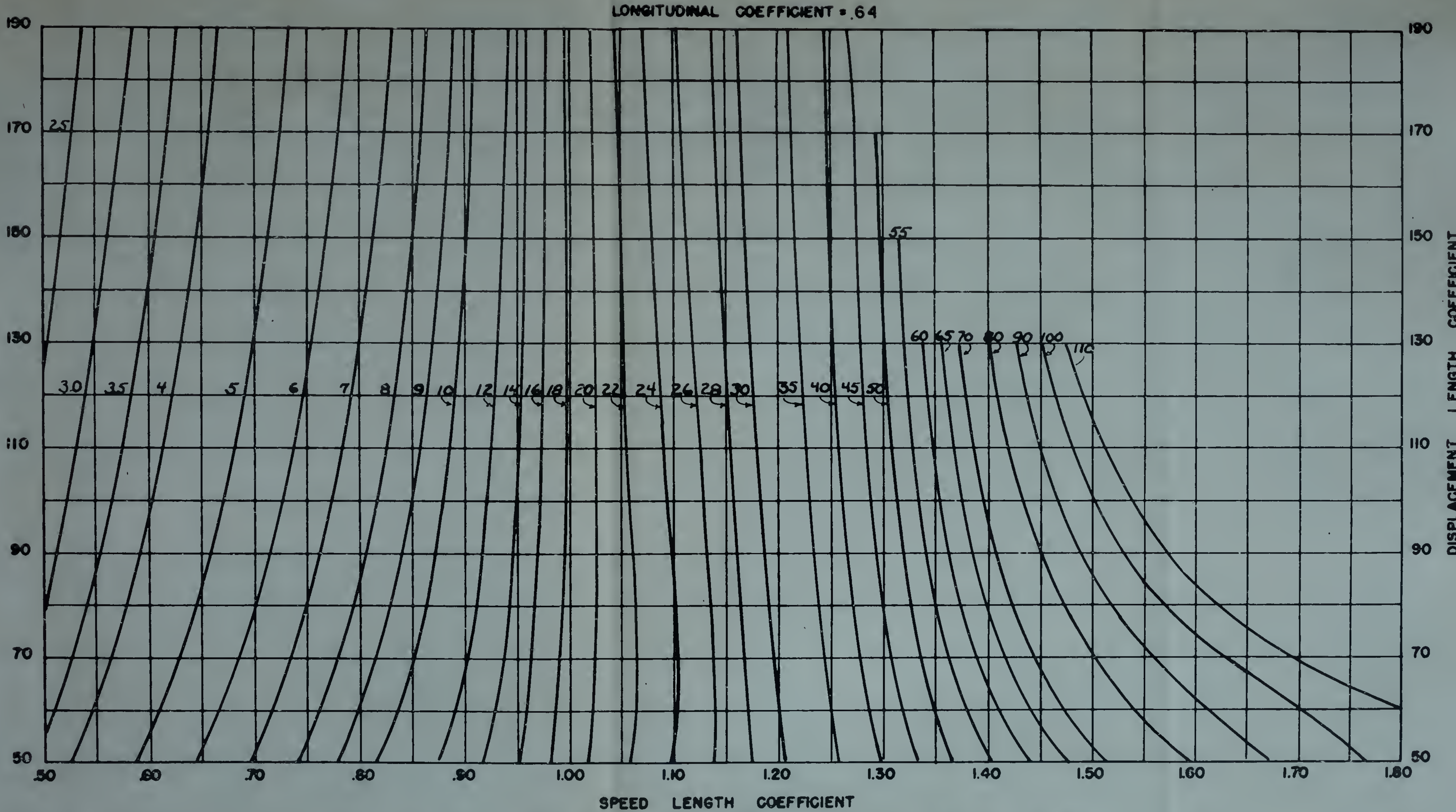
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



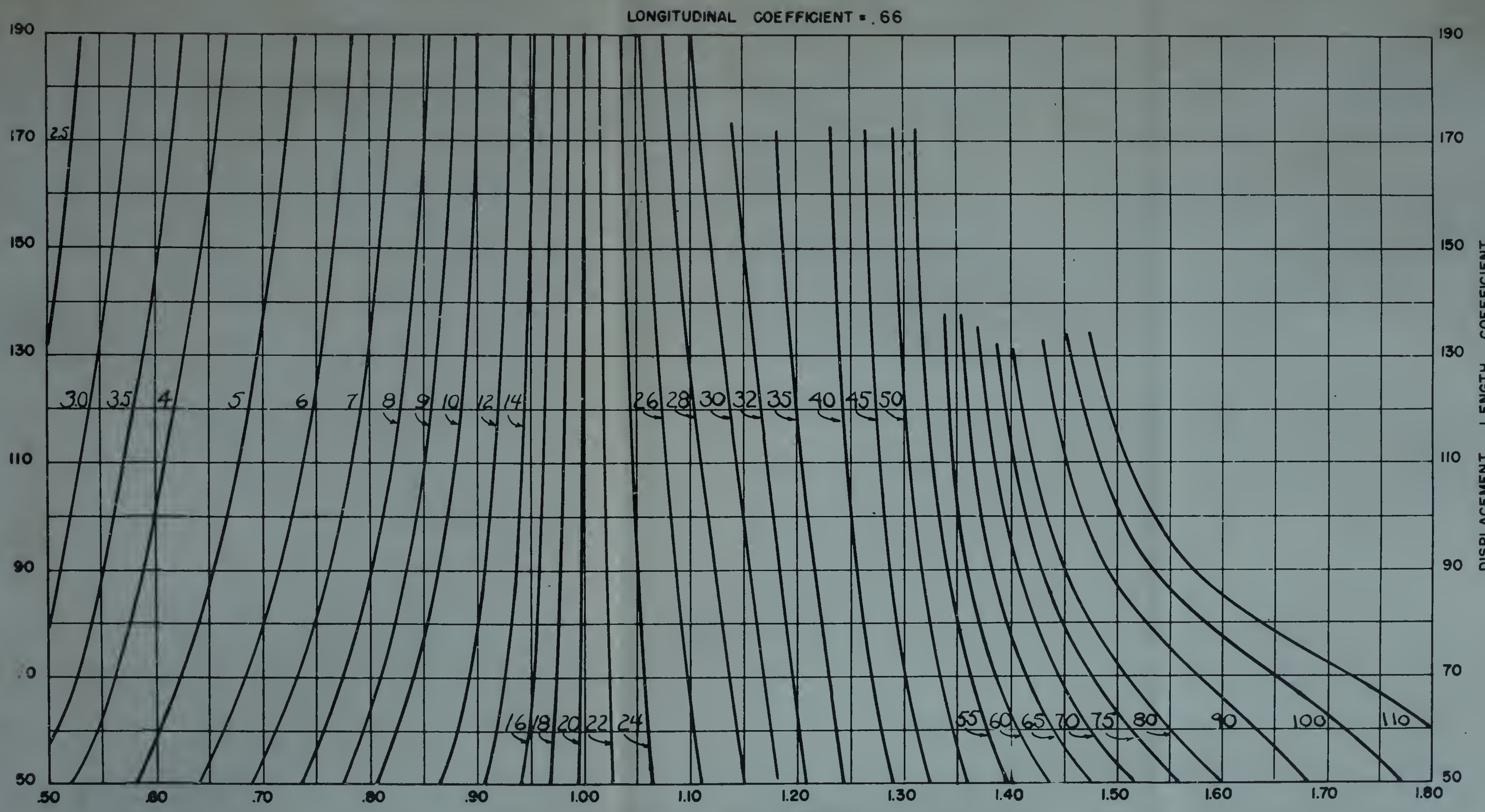
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



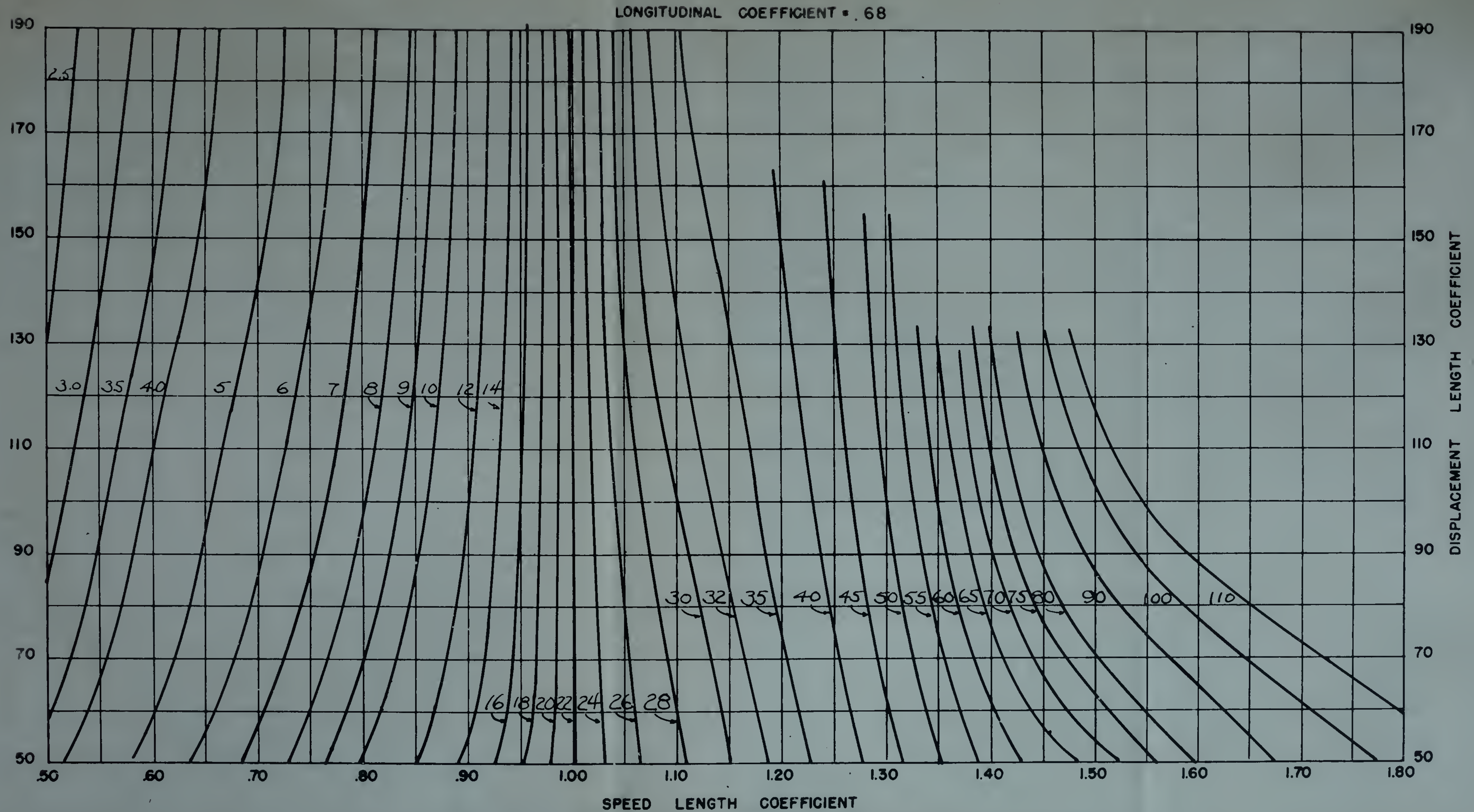
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



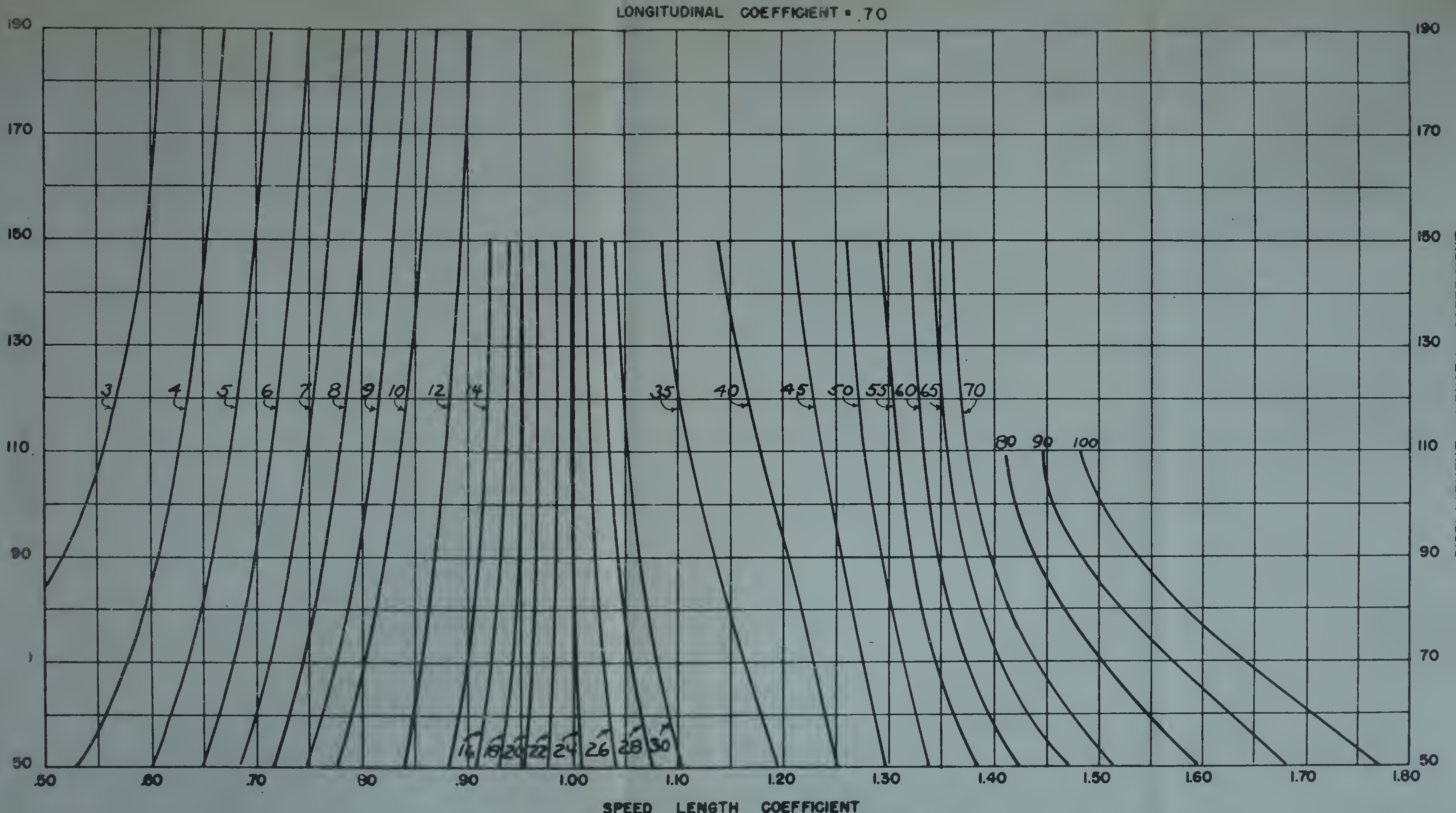
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



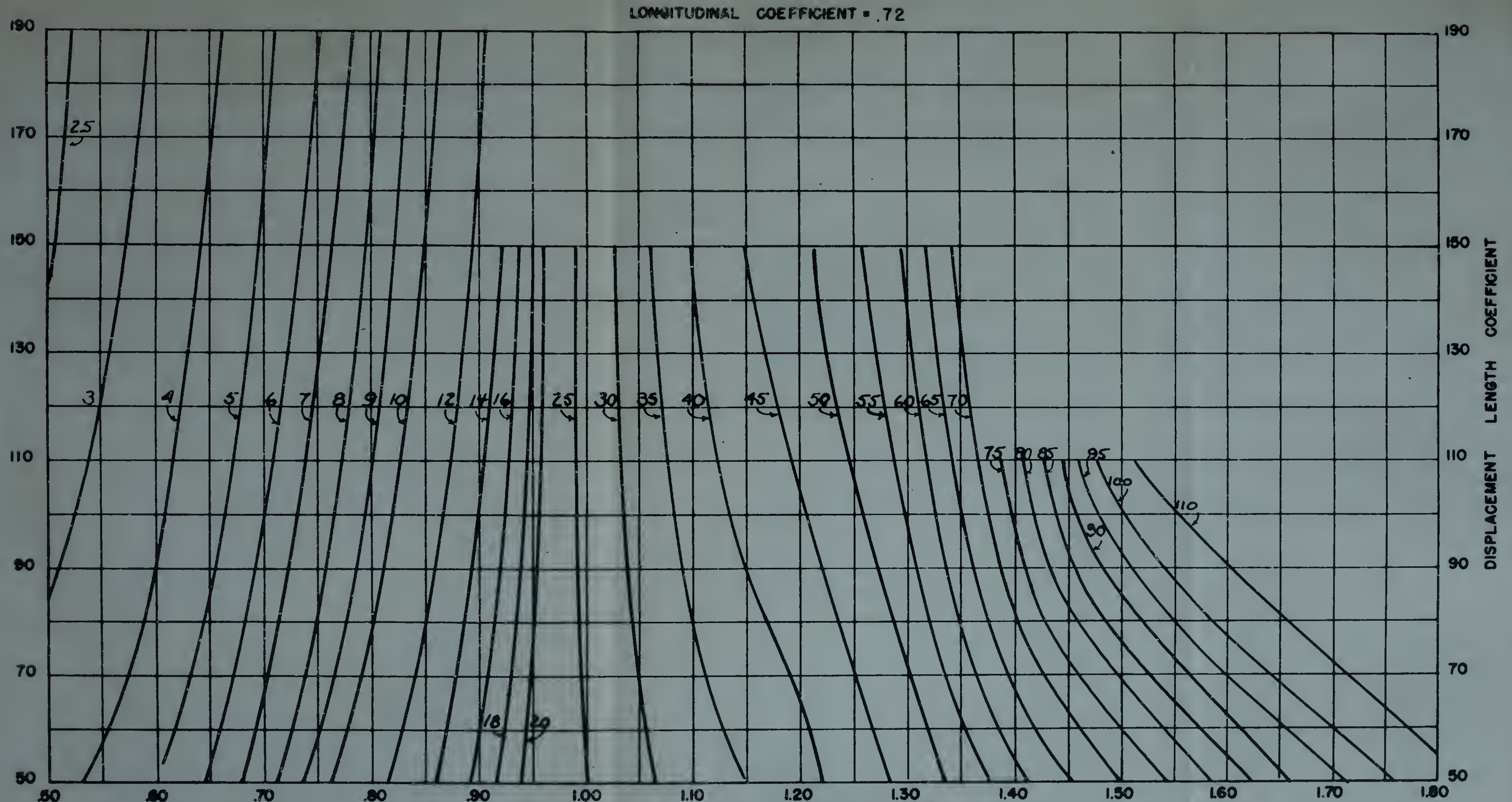
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



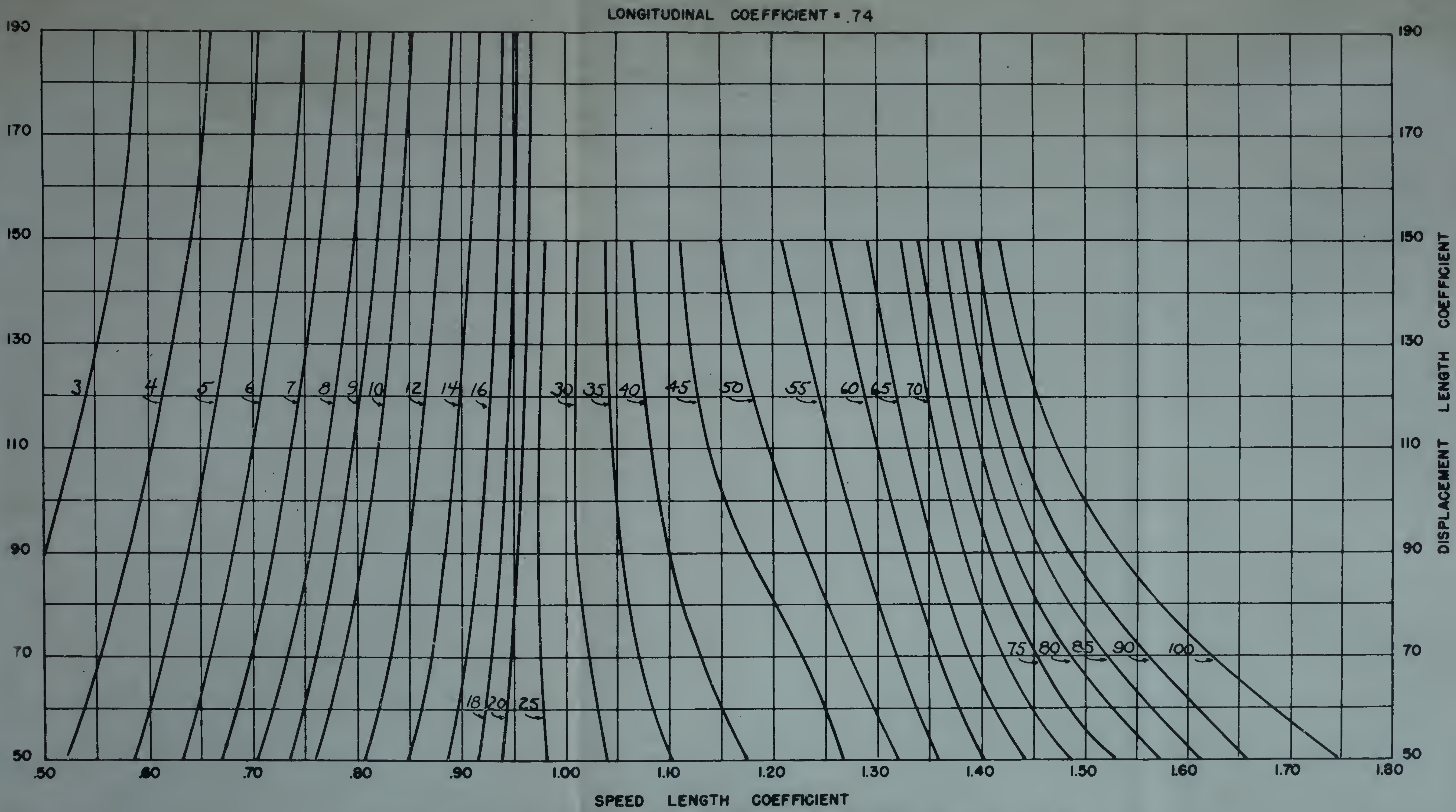
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



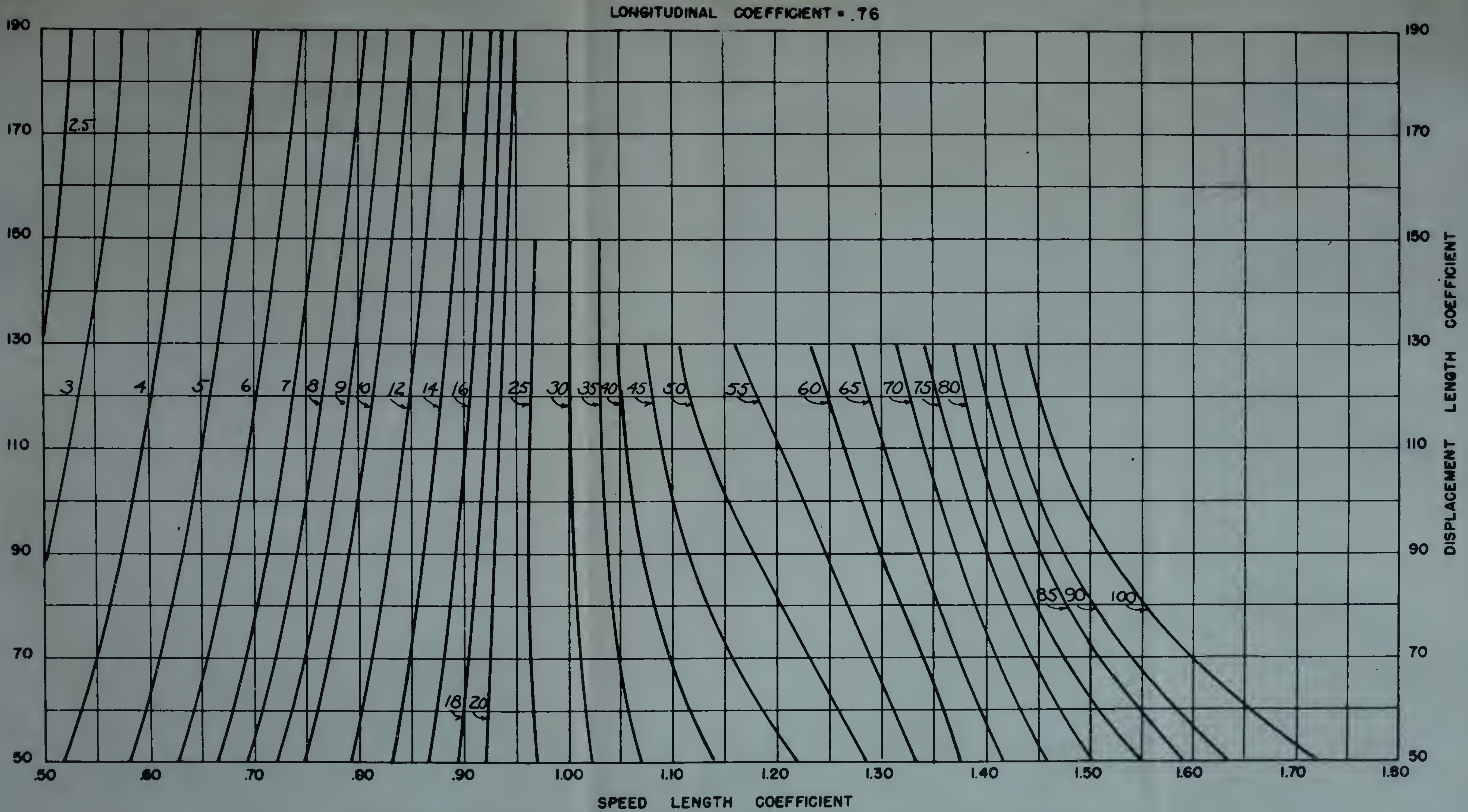
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



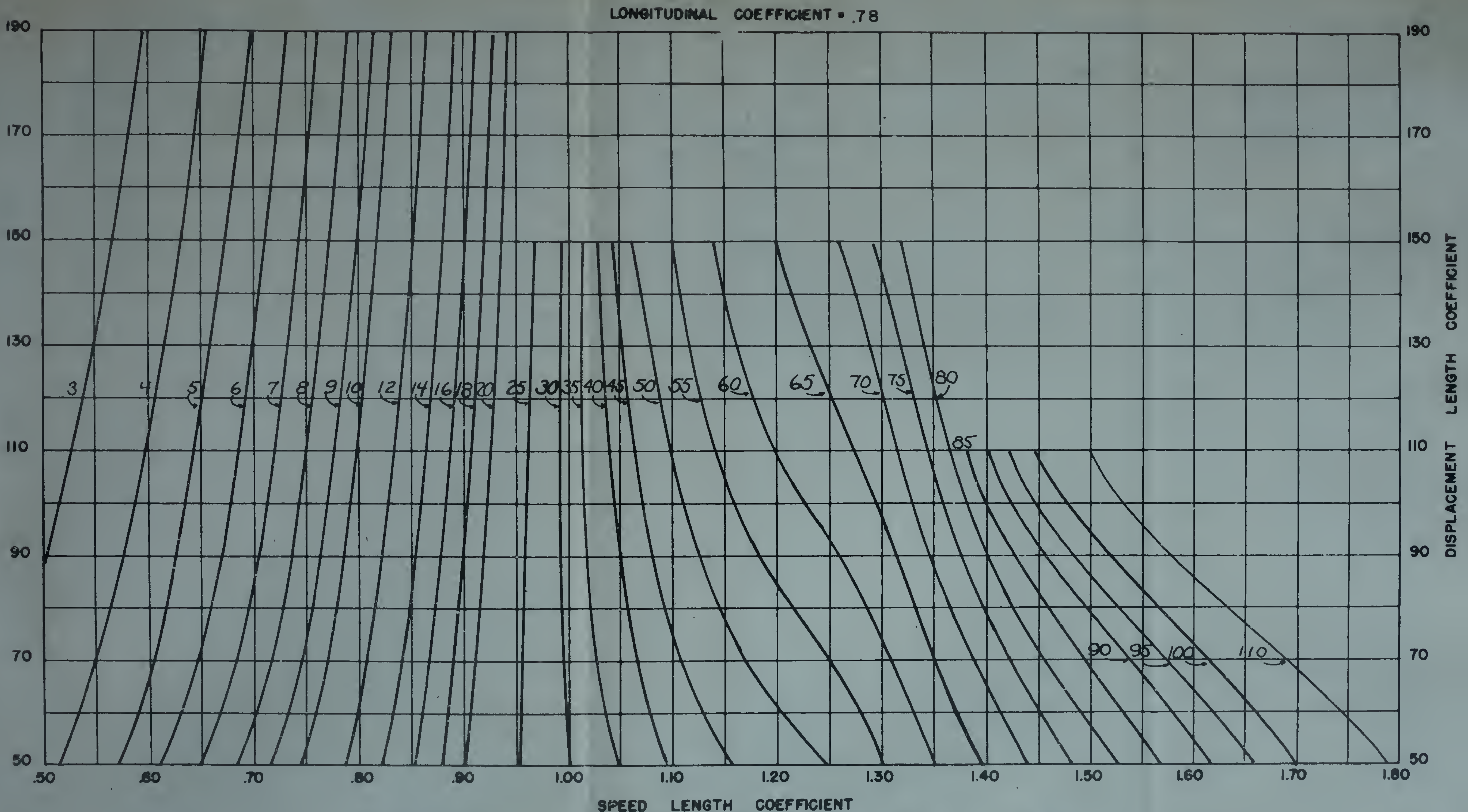
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



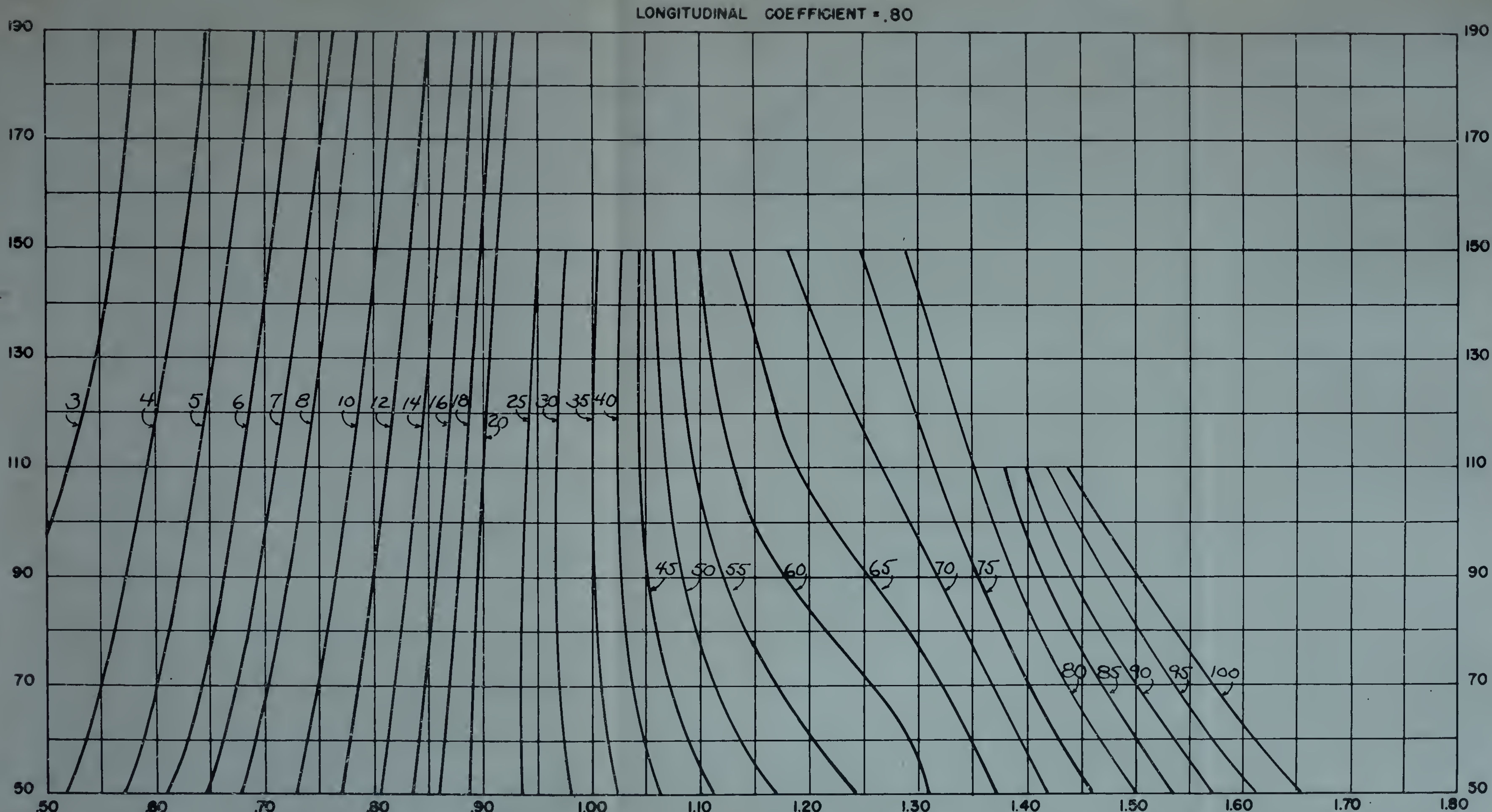
CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25



CONTOURS OF TOTAL RESISTANCE IN POUNDS PER TON OF DISPLACEMENT

Bsn.N.S.-5-10-48-25

DISCUSSION OF RESULTS

A. Criteria

The authors started out to find an approximate method of determining resistance for preliminary design studies. There are two primary criteria to be applied to the results of such a study: (1) Is it accurate enough to be used? and (2) Does it represent any real advantages in time or method of use which make it preferable to the regular method? It is our opinion that both of these criteria are satisfied by these curves.

B. Accuracy

Accuracy of the charts, as mentioned under results, is within the accuracy to be expected of preliminary calculations. In fact, a two percent error in the resistance is within the limits of accuracy of many tests used to determine resistance. It has been said that EHP curves should be drawn with a paint brush instead of a pen, and with this in mind, a one or even two percent variation from Taylor's Series seems quite negligible. Many designs improve on Taylor's Series by special features, such as transom sterns and bulbous bows. These curves are not intended to allow for such variations and are applicable only as far as Taylor's data normally would be used. The appendix includes a table of results (table IV) obtained for comparison from this series and from Taylor for a wide range of hull forms.

C. Advantages

In the calculation of comparative figures and general

use of the curves the authors found that there were advantages in both time and accuracy of use for these curves. The elimination of the awkward four-way interpolation required in Taylor's Series alone makes for simplicity and this, in turn, offers fewer opportunities for error. In the preparation of Table IV for example, when large discrepancies indicated an error in one or the other of the methods, the mistake was almost invariably found in the interpolations of Taylor's Series. There is an appreciable saving in time as well, especially when a number of calculations are to be made.

D. Number of Charts Required

The total number of charts required speaks for itself. The 15 charts here are to be compared to 56 in Taylor. Not only this, but for any specific hull the complete range of data may be obtained from three or four of these new charts owing to the use of $V/\sqrt{L}$ as an abscissa, while all the charts must be used in Taylor. The total number of charts required depends on whether or not it is desired to interpolate between values of ℓ. If it is desired to use the nearest plotted value of ℓ to the hull in question without interpolation, then it is necessary that the increments in ℓ be small. The authors had this in mind when .02 was selected as the increment to be used. In the curves as presented here it is possible to use the nearest plotted value of ℓ without interpolation, as indicated under Results. The magnitude of the error thus introduced will be greatest,

of course, for "median values" of λ (.65, .67, etc.) and it amounts to as much as 5% for values of λ in the vicinity of .75 and $V/\sqrt{L}$ below 1.0. An "average" difference to be expected for "median values" of λ has been found to be about 2%. The effects of this difference can be seen quickly in Table IV, which gives representative values with and without interpolation for comparison to Taylor's Series. If it is especially desirable to limit the total number of charts, negligible error will be introduced by accepting the necessity of interpolation and using values of λ separated by .04 or even .06, in which case the total number of charts required reduces to 7.

The range of values of λ to be covered is also open to some modification. It seems unlikely that .56 would be required for a normal use, although it is presented here for completeness. It is possible to go to higher values of λ than .80 for values of $V/\sqrt{L}$ below 1.00 but this did not seem worthwhile.

In consideration of the number of charts required it is noteworthy that the provision of an additional B/H correction chart would improve the accuracy of the results. The errors from the basic data as shown by table IV run as high as 2½%, much of which comes from the use of mean values of λ in the development of the B/H correction. If we use two charts, one covering values of λ below .70 and one above .70 we can reduce this maximum error from 2½% to about 1½%. The authors feel, however, that the additional complication of an extra correction chart is not worth the gain in

accuracy, since the method is offered primarily for ease and convenience where accuracy is not essential.

E. Conclusion

It is the opinion of the authors that these curves are simpler to handle than the Taylor series. They are certainly more condensed and they are well within the limits of accuracy normally expected for preliminary studies. They are offered for use wherever they may be applicable.

APPENDIX

APPENDIX A

Details of Procedure

1. Range of Hull Forms

As mentioned in the section on procedure a survey of representative characteristics was made in order to decide on the range of coefficients to be covered. Table I is a tabulation of a wide variety of ships in actual service which was the basis for this study. It is felt that this list includes all types likely to be encountered in normal design work.

2. Tabulation of Resistance Data

The data from Taylor's "Speed and Power" was picked off in tabulated form for ease in plotting. Table II is a sample of this form. The originals are all filed in the thesis notebook. The values in any case may be checked directly from Taylor's curves if desired.

3. Development of length correction

In considering the possible methods of providing a correction for variation in length it was decided that a nomogram including length and $V/\sqrt{L}$ would be the best method. These variables were chosen because variations of length from the mean value of 500 ft. will cause an error in the frictional component of Rt only and the proportion of this component in turn depends primarily on $V/\sqrt{L}$ and only secondarily on d and ℓ. In order to eliminate d and ℓ the proportion Rf/Rt, designated x, was averaged for values of ℓ = .56, .64, [illegible], [illegible] and these points plotted vs $V/\sqrt{L}$. An average

TABLE I

TABLE OF REPRESENTATIVE CHARACTERISTICS

SHIP	L	B	H	Δ	V *	B/H **	d	$V/\sqrt{L}$
Battleship	666	108	34	43,000	27	3.18	144	1.05
Battleship	860	108	34	54,000	33	3.18	84.4	1.13
Air. Carrier	820	93	29	34,000	33	3.21	61.2	1.15
Cruiser	564	69.7	23.5	16,000	33	2.95	54.3	1.39
Cruiser	600	63	24	12,700	33	2.63	60.2	1.35
Battlecruiser	790	89.5	31	31,700	33	2.89	64.5	1.18
Destroyer	369	39.3	13	3,100	36	3.02	61.4	1.87
Escort	300	36.8	11	1,800	24	3.35	66.7	1.39
Minesweeper	170	23	6.5	300	16	3.54	60.7	1.23
Minesweeper	215	32	9	850	18	3.55	85.0	1.23
Subchaser	107	17	6	108	22	2.83	86.5	2.12
Tender	520	73.3	23.8	16,700	18	3.18	120	.79
Tender	404	53.3	19.7	8,900	13	2.70	142	.65
Tender	300	41	12	2,400	20	3.42	89	1.16
Repair Ship	520	73.3	19	13,000	19	3.86	90.7	.83
Cargo Ship	415	60	19	5,400	17	3.16	75	.83
Cargo Ship	435	63	25	13,900	16	2.50	167	.77
Cargo Ship	415	60	25	11,500	19	2.40	160	.93
Cargo Ship	416	56.8	27.7	14,200	11	2.10	198	.54
Cargo Ship	255	42.5	20.7	5,200	10	2.05	315	.63
Cargo Ship	390	61	18	8,300	15	3.38	130	.76
Tanker	500	68	30.8	22,400	18	2.20	180	.81
Tanker	503	68	30.2	21,900	16	2.25	177	.71
Tanker	439	58.2	25.5	15,300	11	2.28	191	.53
Tanker	292	48.5	15.3	4,100	14	3.15	[illegible]	.82

*, ** - see next page.

TABLE I (cont.)

SHIP	L	B	H	Δ	V	B/H	d	$V/\sqrt{L}$
Mormacyork	465	69.5	23.3	17,[illegible]00	17	3.00	13[illegible]	.[illegible]
Santa Rita	370	53.2	20	[illegible],700	12	2.66	14[illegible]	.[illegible]
ConteBiancamano	665	66.1	27	24,[illegible]00	20	2.44	96	.[illegible]
Washington	685	86	30.7	33,600	22	2.[illegible]0	[illegible].5	.[illegible]
West Point	660	93.3	32.9	35,500	18	2.85	123	.6[illegible]
Net Layer	440	60.3	18	8,000	14	3.35	93	.[illegible]
Salvage Tug	207	39	13	1,630	17	3.00	86	1.1[illegible]
Seagoing Tug	195	38.5	14.3	1,500	16	2.70	203	1.15

* V is listed here to the nearest knot.

** B/H will vary considerably for cargo vessels with their condition of loading. An effort has been made here to obtain or estimate loaded figures.

TABLE II

SAMPLE FORM USED TO RECORD DATA

ℓ .66
$V/\sqrt{L}$ .90

d	Rr B/H 2.25	Rr B/H 3.75	Rr B/H 3.0	Rf	Rc
50	3.8	4.3	4.05	9.6	13.65
70	4.07	4.7	4.39	8.0	12.39
90	4.25	4.9	4.57	7.05	11.62
110	4.35	5.1	4.73	6.4	11.13
130	4.4	5.2	4.80	5.9	10.70
150	4.5	5.3	4.90	5.5	10.40
170	4.56	5.4	4.98	5.2	10.18
190	4.62	5.45	5.03	4.9	9.93

ℓ .66
$V/\sqrt{L}$ 1.00

d	Rr B/H 2.25	Rr B/H 3.75	Rr B/H 3.0	Rf	Rc
50	8.85	8.9	8.87	11.5	20.37
70	10.3	10.4	10.35	9.75	20.10
90	11.5	11.5	11.5	8.6	20.10
110	12.3	12.2	12.25	7.8	20.05
130	13.1	12.8	12.95	7.2	20.15
150	13.7	13.3	13.5	6.7	20.2
170	14.3	13.7	14.0	6.3	20.3
190	14.8	14.0	14.4	5.95	20.35

line was then drawn through these points to get figure XVIII. The correction for length was then determined as follows: We can write

$$Rt_{corrected} = Rt_{mean} + Rt_{mean}(\text{correction factor}) \qquad (3)$$

In order to find the correction factor to be used here, we note that the length correction (α in Taylor's Fig. 148) is applicable to frictional resistance only. The magnitude of this correction to frictional resistance is $(\alpha - 1)Rf$, and from Fig. XVIII we see that $Rf = Rt(x)$. Combining these we have,

$$\text{Correction} = Rt_{mean}(x)(\alpha - 1) \qquad (4)$$

then from (3) and (4)

$$Rt_{corrected} = Rt_{mean} + Rt_{mean}(x)(\alpha - 1)$$

or

$$Rt_{corrected} = Rt_{mean}\left[1 + x\,(\alpha - 1)\right] \qquad (5)$$

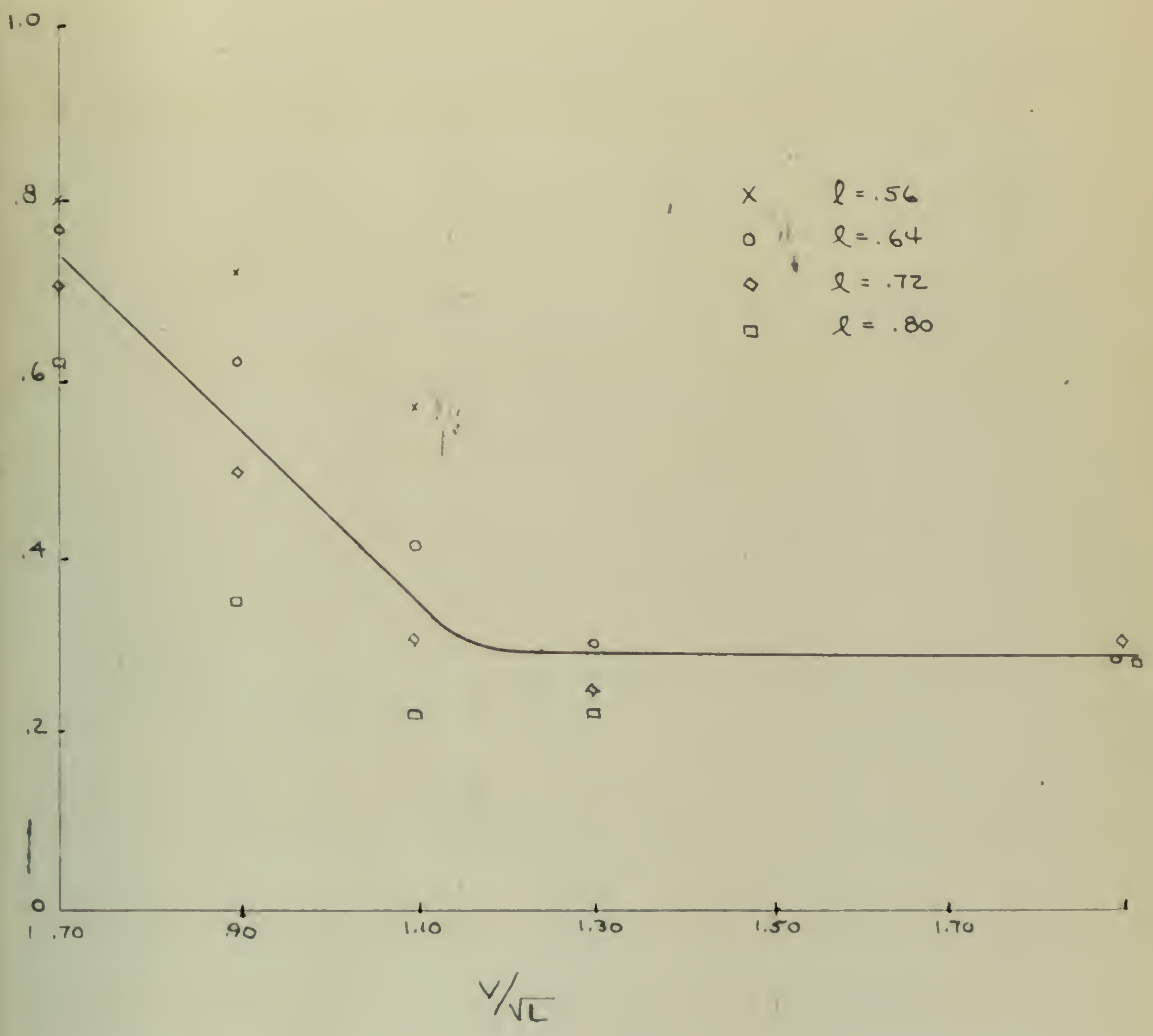
We let the expression $\left[1 + x\,(\alpha - 1)\right]$ be the correction factor A. The values of A are computed from fig. 148 in Taylor and from fig. XVIII herein for various lengths (Table III). The values of A are presented in the form of a nomogram for ready use. This is fig. III in the section on results.

4. <u>Development of the B/H correction</u>

The effect of B/H variation on wetted surface coefficient was ignored because it is a negligibly small quantity, as explained under Procedure. An investigation of the effect on Residual resistance, however, revealed variations in total resistance of -8% to + 15% for extreme values of B/H and showed a correction to be essential if reasonable accuracy was to be obtained. The goal in obtaining such a

FIGURE XVIII

PLOT OF MEAN VALUES OF X
$(X = R_f/R_t)$



JN
5/14/48

TABLE III

COMPUTATION OF A

	$V/\sqrt{T}$		.70	.90	1.00	1.10	1.30	.70	.90	1.00	1.10	1.30
x from Fig. XVIII			.75	.55	.45	.35	.30					
L	α	$(\alpha - 1)$	$(\alpha - 1)\,x$					$A = [1 + (\alpha - 1)\,x]$				
200	1.129	.129	.097	.071	.058	.045	.039	1.097	1.071	1.058	1.045	1.039
300	1.067	.067	.050	.037	.030	.023	.020	1.050	1.037	1.030	1.023	1.020
400	1.027	.027	.020	.015	.012	.010	.008	1.020	1.015	1.012	1.010	1.008
500	1.000	.000	.000	.000	.000	.000	.000	1.000	1.000	1.000	1.000	1.000
600	.979	-.021	-.016	-.012	-.009	-.007	-.006	.984	.988	.991	.993	.994
700	.961	-.039	-.029	-.021	-.018	-.014	-.012	.971	.979	.982	.986	.988
800	.946	-.054	-.041	-.030	-.024	-.019	-.016	.959	.970	.976	.981	.984
900	.933	-.067	-.050	-.037	-.030	-.023	-.020	.950	.963	.970	.977	.980
1000	.921	-.079	-.059	-.043	-.036	-.028	-.024	.941	.957	.964	.972	.976
1100	.911	-.089	-.067	-.049	-.040	-.031	-.027	.933	.951	.960	.969	.973
1200	.902	-.098	-.074	-.054	-.044	-.034	-.029	.926	.946	.956	.966	.971

correction was to obtain a single plot of contours of actual variation in total resistance on coordinates of any two of the primary variables $V/\sqrt{L}$, ℓ, or d. Plots were made of the variation of resistance vs. ℓ for different values of d at several values of $V/\sqrt{L}$. Plots were also made for the variation in resistance with variation of B/H vs. $V/\sqrt{L}$ for different values of d at several values of ℓ. Neither of these attempts showed any possibility of simplification for easy use.

5. The next step in this investigation was to plot variation in resistance for unit variation of B/H vs. d for different values of ℓ and at different values of $V/\sqrt{L}$ (see fig. XIX). It was found that for each value of $V/\sqrt{L}$ the curves for different values of ℓ formed a compact family of curves, through which a mean could be drawn and thus ℓ was eliminated as a variable. These mean curves at different values of $V/\sqrt{L}$ were then combined in a single plot (fig. XX), from which contours of variation could be picked off and plotted on coordinates of d and $V/\sqrt{L}$ in the same manner as the Rc contours of figures V to XVII. The finished plot is given in fig. IV. The method of obtaining it is illustrated by figs. XIX, and XX. The values plotted on the contours represent

$$C' = \frac{Rr_{(B/H\ 3.75)} - Rr_{(B/H\ 3.0)}}{.75} \qquad (6)$$

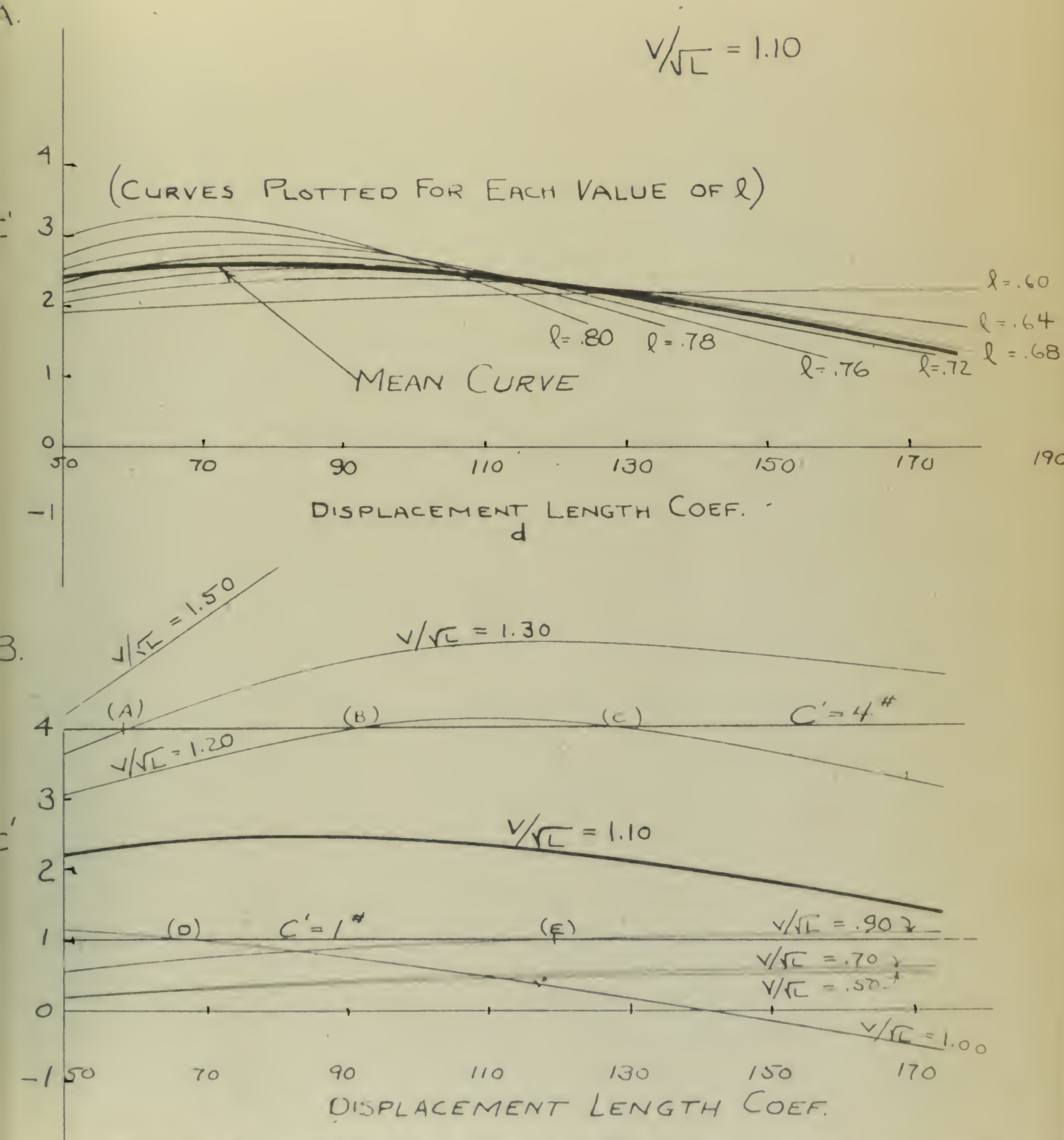
This value was selected in order to simplify the correction to

$$C = (B/H - 3.0)C' \qquad (7)$$

This correction, C, is to be added to the value of Rc obtained

FIGURE XIX

METHOD OF ELIMINATING ℓ AS A VARIABLE IN B/H CORRECTION

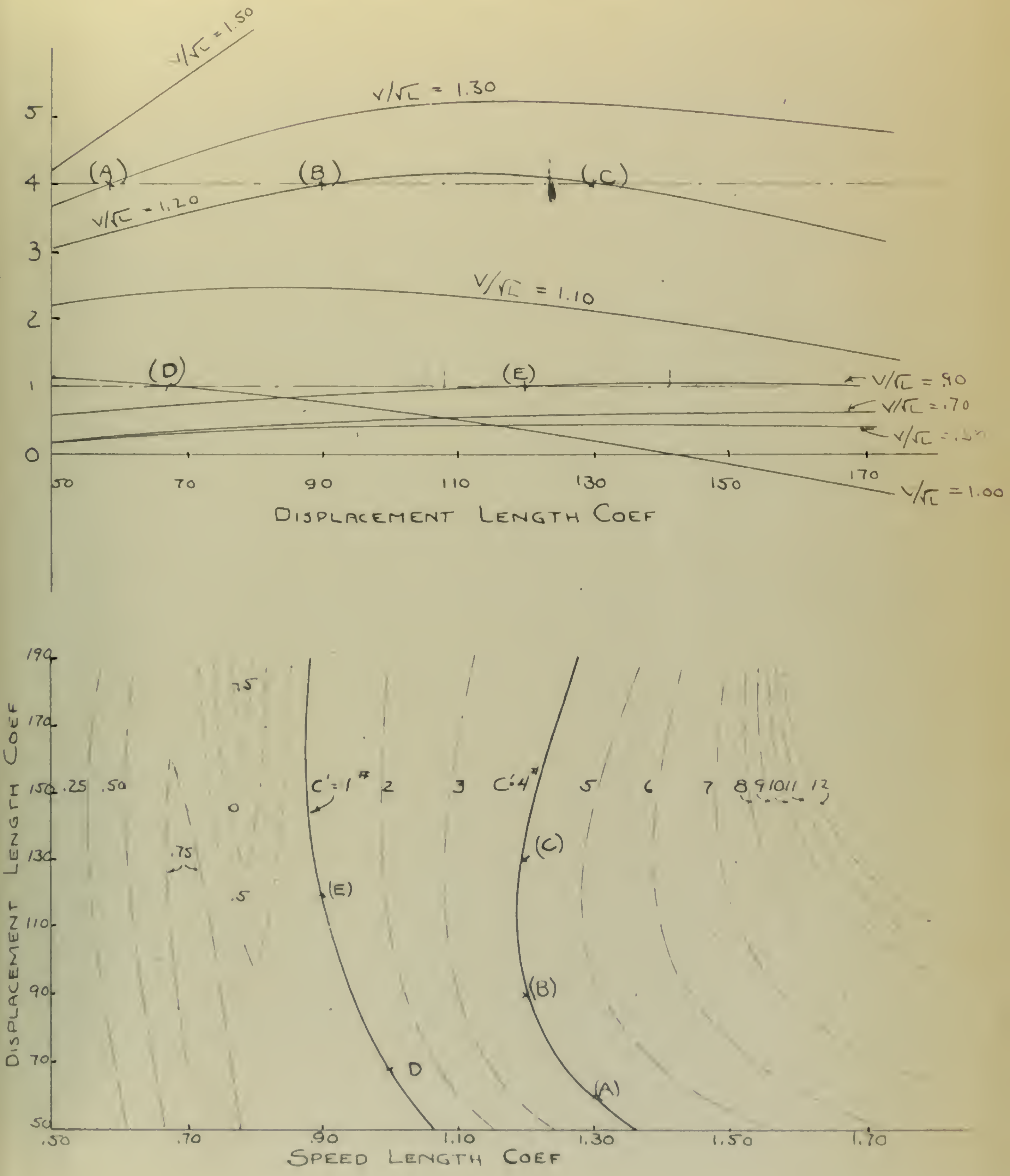


CURVES B OBTAINED BY COMBINING CURVE "A" MEAN CURVES FOR EACH VALUE OF V/√L

WIJ 5/14/48

FIGURE XX

METHOD OF PLOTTING B/H CORRECTION CONTOURS



WN 5/11/48

from figures V to XVII, with the correct algebraic sign as determined by equation (7). In general this correction is additive for values of B/F greater than 3.0 and subtractive for values less than 3.0. The exception will be noted as a small negative area on figure IV.

6. It is to be noted that here again we have developed an "average" correction which will not correct 100% for all forms but will give good results when combined with the other approximations made in this study. As stated before, with no correction for B/F it is possible to introduce errors of as high as 15% of Rt for extreme values of B/F (2.0 or 4.0). With the average correction as given in figure IV, the maximum possible error is reduced to 5%. It should be emphasized that these possible errors are the maximum obtained at extreme values of the coefficients and $V/\sqrt{L}$. The errors to be expected in general use are much less than these figures.

APPENDIX B

Sample Calculations

Calculations for a variety of hulls of normal form have been made for comparison of the Taylor curves and the curves developed in this thesis. The results of these calculations are tabulated in table IV. The calculations themselves are filed in the thesis notebook.

TABLE IV

COMPARATIVE RESISTANCE TABLE

* % difference from Taylor

** % difference from interpolated Thesis value

TYPE HULL	CHARACTERISTICS							TAYLOR	THESIS			
	Δ	L	B	H	V	m	ℓ	Rt	Interpolated Rt	Interpolated % *	Nearest Value Rt	Nearest Value % **
Passenger Liner	40,000	800	96	30.5	26	.956	.625	12.29	12.40	.90	12.32	.33
Passenger Liner	31,300	630	81	32	20	.988	.679	6.92	6.90	.29	6.90	.0
Coast. Pass.&Cargo	11,000	412	60	24.5	15.5	.967	.664	5.87	5.78	1.50	5.77	.17
Cargo Ship	15,000	425	57	28	12	.992	.782	2.91	2.88	1.03	2.88	.0
Cargo Ship	10,500	385	55	24.5	13	.986	.724	4.02	4.00	.50	3.98	.50
Tanker	21,000	486	68	30	13.8	.978	.774	3.56	3.49	1.96	3.43	1.71
Aircraft Carrier	33,600	856	93	27	33	.930	.585	21.5	22.0	2.25	21.8	1.00
Battle Cruiser	31,700	790	86	30	32	.923	.590	21.67	22.2	2.30	21.7	2.1
Cruiser	13,560	700	74	24	33	.930	.625	33.35	34.2	2.50	34.0	.6
Cruiser	11,600	570	63.5	19.5	32.5	.920	.623	54.5	54.6	.20	54.6	.0
Aux. Air. Carrier	9,630	490	65	19	18	.965	.580	7.88	8.00	1.50	8.0	.0
Gunboat	2,290	308	41	12.5	20	.989	.570	22.63	23.20	2.50	22.7	2.2
Coast Guard Cutter	2,350	312	41	13	20	.985	.579	[illegible]	21.00	1.7	21.80	.0
Escort	1,500	300	30.3	10	22	.780	.620	39.4	39.4	2.50	39.4	.0
Minelayer	[illegible]	[illegible]	[illegible]	17.5	20	.963	.595	[illegible]	12.35	1.6	12.75	[illegible]

APPENDIX C

Bibliography

(1) Taylor, D. W., "The Speed and Power of Ships." United States Government Printing Office: 1943.

(2) Lachowski, M. M., "Notes on Preliminary Ship Design." Marine Engineering and Shipping Review, March 1947.